LCA Methodology

Human Health Damages due to Indoor Sources of Organic Compounds and Radioactivity in Life Cycle Impact Assessment of Dwellings

Part 2: Damage Scores

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Preamble. In this series of two papers, a methodology to calculate damages to human health caused by indoor emissions from building materials is presented and applied. **Part 1** presents the theoretical foundation of the indoor emission methodology developed, as well as characterisation factors calculated for 36 organic compounds, radon and gamma radiation. **Part 2** calculates damage scores of building materials with the characterisation factors presented in part 1. The relevancy of including indoor air emission in the full damage scores at a material level and a dwelling level is also quantified and discussed.

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Abstract

Goal, Scope and Background. In industrialized countries such as the Netherlands, the concentration of pollutants originating from building materials in the indoor environment has shown an increasing trend during the last decades due to improved isolation and decreased ventilation of dwellings. These pollutants may give rise to negative impacts on human health, ranging from irritation to tumours. However, such negative impacts on health are not included in current life cycle assessments of dwellings. In this study, damages to the health of occupants caused by a number of organic compounds and by radioactivity emitted by building materials, including those due to indoor exposure, have been calculated for a number of categories of common building materials. The total damage to human health due to emissions occurring in the use phase of the Dutch reference dwelling is compared with the total damage to human health associated with the rest of the life cycle of the same dwelling.

Methods. Human health damage scores per kilogram of building material for compartments of the Dutch reference dwelling have been calculated using the methodology described in part I of this research. This methodology includes the calculation of the fate, effect and damage factors, based on disability adjusted life years (DALYs), and has been applied assuming average concentrations of pollutants in building materials. Damage scores for health impacts of exposure to pollutants emitted during the production and the disposal phase of the same building materials were calculated using standard LCIA methodology.

Results and Discussion. Human health damage scores due to emissions of pollutants occurring in the use phase of building materials applied at the first or second floor are up to 20 times lower or higher than the corresponding damage scores associated with the rest of the life cycle of the same building materials. The damage scores due to emissions occurring in the use phase of building materials applied in the crawlspace are up to 10^5 times lower than those of building materials applied in the other compartments. The total damage to human health due to emissions occurring in the use phase of the Dutch reference dwelling has the same order of magnitude as the total damage to human health associated with the rest of the life cycle of the same dwelling. At a dwelling level, radon and gamma radiation are dominant in the human health damage score among the pollutants studied.

Conclusion. Health damages due to indoor exposure to contaminants emitted by building materials cannot be neglected for several materials when compared with damage scores associated with the rest of the life cycle of the same building materials. Indoor exposure to pollutants emitted by building materials should be included in the life cycle assessment of dwellings in order to make the assessment better reflect full impact of the life cycle.

Keywords: Building materials; dwellings; gamma radiation; human health damages; indoor pollutants; life cycle impact assessment; organic compounds; radioactivity; radon

Introduction

During recent decades in industrialized countries such as the Netherlands, houses have been increasingly insulated to prevent heat losses. A side effect thereof is the occurrence of higher concentrations of indoor pollutants that may cause health risks for occupants. Much research has been done on indoor emissions and the negative effects on health following from exposure to e.g. formaldehyde emitted from chipboard and radon emitted from stony materials. In the Netherlands, it has for instance been estimated that 800 persons per year die of lung cancer due to indoor exposure to radiation originating from stony building materials [1]. However, in existing life cycle impact assessment (LCIA) methodologies for dwellings, such health risks are not taken into account [2,3].

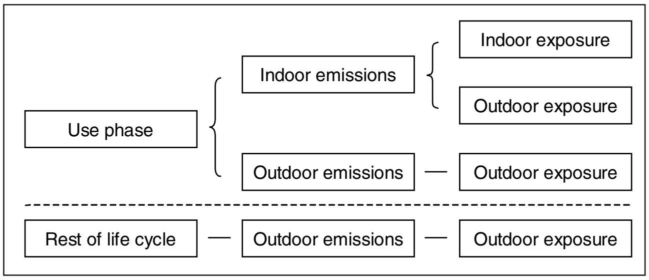

Fig. 1: Life cycle phases of dwellings, emissions and exposures

Emissions of and exposures to contaminants occur in all phases of the dwelling life cycle. This is illustrated in **Fig. 1**. In this study, a division is made between emissions occurring in the use phase and emissions occurring in the rest of the dwelling life cycle. In the use phase, building materials emit contaminants directly to both indoor air (indicated as indoor emissions) and outdoor air (indicated as outdoor emissions; examples of outdoor sources are outdoor constructions, roofs and façades). Indoor emissions lead to indoor exposure and to outdoor exposure when the substances are transported to outdoor air by ventilation. Outdoor emissions lead only to outdoor exposure. In this article, health damage scores due to indoor and outdoor emissions occurring in the use phase of a number of building materials applied in the Dutch reference dwelling [4,5] are calculated based on characterisation factors determined in the first part of this research [6].

In the rest of the life cycle, emissions of substances take place to outdoor air only. These emissions lead to outdoor exposure. Damage scores associated with the rest of the life cycle of the same materials are calculated by standard LCIA methodology [7].

The total health damage scores due to emissions occurring in the use phase of the reference dwelling and those associated with the rest of the life cycle of the same dwelling are also compared. For indoor exposure 8 organic compounds, radon and gamma radiation are considered (see Table 1). The Dutch reference dwelling is a one-family row house, constructed with concrete floors, facades of bricks and sand-lime bricks and inner walls made of gypsum and sand-lime bricks [4,5]. The dwelling is supposed to be used by three occupants, and average weather conditions for the Netherlands are used in the calculations. Damages to human health are expressed in disability adjusted life years (DALYs) [8–10].

1 Methodology

1.2 Calculation procedure

In the LCIA methodology used here, damage to human health is calculated per kilogram building material. Combining human health damages associated with the use phase and with the rest of the life cycle of the building material, the total damage score can be calculated by Eq. (1):

$$DS_p = DS_{p,u} + DS_{p,l} \tag{1}$$

where DS_p is the total human damage score for building material p ($DALY \cdot kg_p^{-1}$); $DS_{p,u}$ is the total human damage score due to the emissions occurring in the use phase of building material p ($DALY \cdot kg_p^{-1}$); and $DS_{p,l}$ is the total human damage score associated with the rest of the life cycle of building material p ($DALY \cdot kg_p^{-1}$).

Characterisation factors form the link between compound (activity) concentrations and total damage to human health [11]. The damage score due to the emissions occurring in the use phase of building material p can be calculated by Eq. (2):

$$DS_{p,u} = \sum_x M_{x,p} \cdot Q_x \tag{2}$$

where $M_{x,p}$ is the (activity) concentration of compound x in building material p or the total amount of radon exhaled during the lifetime of building material p ($kg \cdot kg_p^{-1}$ or $Bq \cdot kg_p^{-1}$); and Q_x is the characterisation factor of compound x (e.g. $DALY \cdot kg^{-1}$ or $DALY \cdot Bq^{-1}$).

The damage score associated with the rest of the life cycle of building material p can be calculated using the Eco-Indicator 99 methodology [10]. Inventory data to calculate these damage scores are taken from the IVAM LCA Database [12].

On a dwelling level, the total damage score can be calculated by Eq. (3):

$$DS_b = \sum_p X_{p,b} \cdot DS_p \tag{3}$$

where DS_b is the total human health damage score for building b (DALY); and $X_{p,b}$ is the total material input of building material p in building b (kg).

1.2 Characterisation factors

The characterisation factors for the contaminants have been calculated in part I of this research [6]. Fate factors have been calculated based on indoor and outdoor intake fractions, dose conversion factors or extrapolation from measurements. Effect factors have been calculated based on unit risk factors, (extrapolated) effect doses or linear relationship between dose and cancer cases. Damage factors are based on disability adjusted life years (DALYs).

For the hazardous substances emitted from the building materials into the reference dwelling, the characterisation factors for emissions in each of the three compartments of the dwelling and for emissions directly to the outdoor air during the use phase of the building material are given in **Table 1** [6].

1.3 Concentrations in building materials

The concentration of an organic compound in building material p can be specified as shown in Eq. (4):

$$M_{x,p} = C_{x,p} \cdot df_p \tag{4}$$

where $C_{x,p}$ is the default concentration of organic compound x in building material p ($kg \cdot kg_p^{-1}$); and df_p is the distribution factor for building material p (–).

Table 1: Characterisation factors for several substances emitted into the reference dwelling occupied by three persons

Substance	CAS-nr	Unit	Characterisation factor			
			$Q_{x,c}$ [a]	$Q_{x,1}$	$Q_{x,2}$	$Q_{x,o}$
Organic compounds						
2-Butoxy ethanol	111-76-2	$DALY{\cdot}kg^{-1}$	$1.1{\cdot}10^{-6}$	$2.3{\cdot}10^{-4}$	$2.7{\cdot}10^{-4}$	$9.5{\cdot}10^{-7}$
Formaldehyde	50-00-0	$DALY{\cdot}kg^{-1}$	$8.8{\cdot}10^{-6}$	$1.2{\cdot}10^{-2}$	$1.4{\cdot}10^{-2}$	$3.3{\cdot}10^{-6}$
Propylene glycol monomethyl ether	107-98-2	$DALY{\cdot}kg^{-1}$	$7.9{\cdot}10^{-7}$	$1.7{\cdot}10^{-6}$	$1.9{\cdot}10^{-6}$	$7.9{\cdot}10^{-7}$
Styrene	100-42-5	$DALY{\cdot}kg^{-1}$	$2.6{\cdot}10^{-6}$	$9.4{\cdot}10^{-4}$	$1.1{\cdot}10^{-3}$	$2.1{\cdot}10^{-6}$
Toluene	108-88-3	$DALY{\cdot}kg^{-1}$	$1.4{\cdot}10^{-6}$	$1.4{\cdot}10^{-4}$	$1.7{\cdot}10^{-4}$	$1.4{\cdot}10^{-6}$
Triethyl amine	121-44-8	$DALY{\cdot}kg^{-1}$	$1.6{\cdot}10^{-7}$	$3.3{\cdot}10^{-4}$	$3.9{\cdot}10^{-4}$	$3.8{\cdot}10^{-9}$
Vinyl chloride	75-01-4	$DALY{\cdot}kg^{-1}$	$3.2{\cdot}10^{-6}$	$1.8{\cdot}10^{-3}$	$2.1{\cdot}10^{-3}$	$2.3{\cdot}10^{-6}$
Xylenes	1330-20-7	$DALY{\cdot}kg^{-1}$	$2.4{\cdot}10^{-6}$	$2.2{\cdot}10^{-5}$	$2.6{\cdot}10^{-5}$	$2.4{\cdot}10^{-6}$
Radon	10043-92-2	$DALY{\cdot}Bq^{-1}$	$2.4{\cdot}10^{-11}$	$1.9{\cdot}10^{-10}$	$2.3{\cdot}10^{-10}$	$2.4{\cdot}10^{-11}$
Gamma-radiating elements [b]						
^{226}Ra	13982-63-3	$DALY{\cdot}Bq^{-1}$	0	$1.8{\cdot}10^{-8}$	$1.1{\cdot}10^{-8}$	0
^{232}Th	7440-29-1	$DALY{\cdot}Bq^{-1}$	0	$2.0{\cdot}10^{-8}$	$1.2{\cdot}10^{-8}$	0
^{40}K	13966-00-2	$DALY{\cdot}Bq^{-1}$	0	$1.6{\cdot}10^{-9}$	$9.4{\cdot}10^{-10}$	0

[a] $Q_{x,a}$ = Characterisation factor of compound *x* emitted to compartment *a* (crawlspace (*c*), first floor (*1*) or second floor (*2*) or outdoor (o))
[b] Default lifetime of building material = 75 years; this has been corrected for in the calculations in this study (see formula (6))

The distribution factor df_p reflects the distribution of the emissions over the compartments. When a building material is applied in a wall between two compartments (e.g. the floor between the first and second floor), half of the concentration of the compounds considered is attributed to one of the compartments and half to the other. When a building material is applied in a wall between a compartment and outdoor space, half of the concentration of the compounds considered is attributed to the compartment and half of the concentration is regarded as directly contributing to an outdoor emission.

For radon, the total amount of radon exhaled during the lifetime of building material p is used instead of activity concentration. The total amount of radon exhaled during the lifetime of building material p can be calculated by Eq. (5):

$$M_{Rn,p} = ER_{Rn,p} \cdot LT_p \cdot df_p \tag{5}$$

where $ER_{Rn,p}$ is the radon exhalation rate of building material p ($Bq{\cdot}kg_p^{-1}{\cdot}y^{-1}$); and LT_p is the lifetime of building material p (y).

The activity concentration of gamma-radiating elements in building material p is corrected for the default building material lifetime of 75 year used in the calculation of the characterisation factors [6] and can be calculated by Eq. (6):

$$M_{x,p} = AC_{x,p} \cdot df_p \cdot \frac{LT_p}{75} \tag{6}$$

where $AC_{x,p}$ is the activity concentration of gamma-radiating element x in building material p ($Bq{\cdot}kg_p^{-1}$).

For a number of common building material categories, average (activity) concentrations of organic compounds and gamma-radiating elements in and total radon exhalation of building materials were derived (**Table 2**). When a building material emits radon or gamma radiation, the lifetime of the building material is also mentioned. The concentrations are given using a distribution factor df_p of 1.

1.4 Material input for dwelling

The total amounts of building materials present in the reference dwelling are given in **Table 3**. These amounts include multiple applications of materials (e.g. replacements for maintenance) and losses during building or maintenance. The materials lost in this way do not emit contaminants during the use phase, so for these materials only the damage to human health associated with the rest of the life cycle is taken into account. The amounts also take into account the distribution factors *df* by assigning a value of 0.5 to the amounts for both compartments when a material is applied in a construction separating two compartments. The compartment 'outdoor' refers to materials emitting contaminants directly to the outdoor air (e.g. outdoor constructions, part of façades and roofs). The compartment 'soil' refers to materials applied in the soil (sand, piles and outdoor drains), as to which we assume that the emission to outdoor air during the use phase is negligible.

Table 2: Average concentration of contaminants and total radon exhalation of common building material categories

Category	Material	Lifetime (y) [5]	Substances	(Activity) concentration, total exhalation	Unit	Reference
	Stony materials					
1	Bricks, cement, mortar and ceramics[a]	75	Radon	$4.7\cdot10^{3}$	$Bq\cdot kg_p^{-1}$	[13]
			^{226}Ra	46	$Bq\cdot kg_p^{-1}$	[13]
			^{232}Th	47	$Bq\cdot kg_p^{-1}$	[13]
			^{40}K	519	$Bq\cdot kg_p^{-1}$	[13]
2	Concrete cellular[b]	75	Radon	$4.3\cdot10^{3}$	$Bq\cdot kg_p^{-1}$	[13]
			^{226}Ra	10	$Bq\cdot kg_p^{-1}$	[13]
			^{232}Th	7.6	$Bq\cdot kg_p^{-1}$	[13]
			^{40}K	179	$Bq\cdot kg_p^{-1}$	[13]
3	Concrete other[c]	75	Radon	$5.5\cdot10^{3}$	$Bq\cdot kg_p^{-1}$	[13]
			^{226}Ra	20	$Bq\cdot kg_p^{-1}$	[13]
			^{232}Th	17	$Bq\cdot kg_p^{-1}$	[13]
			^{40}K	115	$Bq\cdot kg_p^{-1}$	[13]
4	Glass[d]	25	^{226}Ra	12	$Bq\cdot kg_p^{-1}$	[14]
			^{232}Th	3	$Bq\cdot kg_p^{-1}$	[14]
			^{40}K	120	$Bq\cdot kg_p^{-1}$	[14]
5	Glass wool[e]	75	Formaldehyde	$7.5\cdot10^{-4}$	$kg\cdot kg_p^{-1}$	[12]
			^{226}Ra	12	$Bq\cdot kg_p^{-1}$	[14]
			^{232}Th	3	$Bq\cdot kg_p^{-1}$	[14]
			^{40}K	120	$Bq\cdot kg_p^{-1}$	[14]
6	Gypsum[f]	60	Radon	$3.6\cdot10^{3}$	$Bq\cdot kg_p^{-1}$	[13]
			^{226}Ra	6.1	$Bq\cdot kg_p^{-1}$	[13]
			^{232}Th	2.2	$Bq\cdot kg_p^{-1}$	[13]
			^{40}K	11	$Bq\cdot kg_p^{-1}$	[13]
7	Rock wool[g]	75	Formaldehyde	$7.5\cdot10^{-4}$	$kg\cdot kg_p^{-1}$	[12,15]
			^{226}Ra	46	$Bq\cdot kg_p^{-1}$	[13]
			^{232}Th	47	$Bq\cdot kg_p^{-1}$	[13]
			^{40}K	519	$Bq\cdot kg_p^{-1}$	[13]
8	Sand-lime bricks[h]	75	Radon	$5.9\cdot10^{3}$	$Bq\cdot kg_p^{-1}$	[13]
			^{226}Ra	11	$Bq\cdot kg_p^{-1}$	[13]
			^{232}Th	9.3	$Bq\cdot kg_p^{-1}$	[13]
			^{40}K	187	$Bq\cdot kg_p^{-1}$	[13]
	Wooden materials					
9	Glued wood (e.g. chipboard, hardboard)[i]	20	Formaldehyde	$1.0\cdot10^{-4}$	$kg\cdot kg_p^{-1}$	[16]
			^{226}Ra	11	$Bq\cdot kg_p^{-1}$	[14]
			^{232}Th	4	$Bq\cdot kg_p^{-1}$	[14]
			^{40}K	26	$Bq\cdot kg_p^{-1}$	[14]
10	Natural wood	30	^{226}Ra	11	$Bq\cdot kg_p^{-1}$	[14]
			^{232}Th	4	$Bq\cdot kg_p^{-1}$	[14]
			^{40}K	26	$Bq\cdot kg_p^{-1}$	[14]
	Paints and glues					
11	Water-based acrylic wall paint	[l]	Propylene glycol monomethyl ether	0.01	$kg\cdot kg_p^{-1}$	[17]
12	Organic solvent-based wall paint[j]	[l]	Xylene	$5.5\cdot10^{-3}$	$kg\cdot kg_p^{-1}$	[15,18]
13	Water-based acrylic wood paint	[l]	2-Butoxy ethanol	0.03	$kg\cdot kg_p^{-1}$	[17]
			Propylene glycol monomethyl ether	0.02	$kg\cdot kg_p^{-1}$	[17]
			Triethyl amine	$5.0\cdot10^{-3}$	$kg\cdot kg_p^{-1}$	[17]
14	Organic solvent-based alkyd wood paint[j]	[l]	Xylene	$5.5\cdot10^{-3}$	$kg\cdot kg_p^{-1}$	[15,18]
15	Epoxy glue	[l]	Toluene	0.13	$kg\cdot kg_p^{-1}$	[15]
	Plastics					
16	Polystyrene	[l]	Styrene	$1.0\cdot10^{-5}$	$kg\cdot kg_p^{-1}$	[19]
17	Polyvinyl chloride[k]	[l]	Vinyl chloride	$1.0\cdot10^{-3}$	$kg\cdot kg_p^{-1}$	[20]

[a] ρ (density) = 1498 $kg\cdot m^{-3}$; thickness = 0.05 m; [b] ρ = 593 $kg\cdot m^{-3}$; thickness = 0.10 m; [c] ρ = 2375 $kg\cdot m^{-3}$; thickness = 0.20 m; [d] no data about radon exhalation available; [e] 0,075 kg ureaformaldehyde/kg glass wool; assumed 1% free formaldehyde in ureaformaldehyde present in glass wool; no data about radon exhalation available; [f] ρ = 843 $kg\cdot m^{-3}$; thickness = 0.07 m; [g] Assumed: formaldehyde concentration same as in glass wool; no data about radon exhalation available; [h] ρ = 1748 $kg\cdot m^{-3}$; thickness = 0.08 m; [i] Formaldehyde concentration according to Dutch standard; [j] 46% white spirit containing 1.2% xylene; [k] Vinyl chloride concentration according to European standard; according to several current material safety data sheets for current commercial products this is the maximum percentage present; [l] Not relevant: no radon or gamma radiation emitted

Table 3: Total amount of building materials present in reference dwelling [5]

Material	Category	Amount (kg)				
		Crawl space	First floor	Second floor	Outdoor[a]	Soil[b]
Acrylic paint	13	–	15	31	–	–
Acrylonitrile-butadiene-styrene		–	1.1	7.6	–	–
Alkyd paint	14	–	13	9.5	22	–
Aluminium		–	13	120	17	–
Anodising layer		–	0.042	0.090	0.13	–
Bitumen		–	–	–	83	–
Brass		–	12	32	–	–
Bricks	1	–	1400	1700	3100	–
Cardboard		–	52	96	–	–
Cast iron		–	–	15	–	–
Ceramics	1	–	420	840	100	–
Chipboard	9	–	470	–	–	–
Chloroprene		–	–	1.1	–	–
Concrete	3	17000	17000	37000	13000	7800
Copper		4.4	9.5	82	–	–
Copper, primary		–	11	16	–	–
Electronics		–	–	8.4	–	–
Enamel		–	2.3	3.1	–	–
Ethylene propylene dipolymer		–	1.1	2.0	–	–
Expanded polystyrene	16	81	81	77	74	–
Glass	4	–	220	240	450	–
Glass wool	5	–	–	0.68	–	–
Glue	15	–	39	46	–	–
Glue, sand-lime bricks	1.15	–	280	340	44	–
Glue, water-based		–	–	2.9	–	–
Gypsum	6	–	2200	2400	–	–
Gypsum plaster	6	–	330	510	66	–
Hardboard	9	–	200	130	–	–
Lead		–	12	2.9	15	–
Meranti	10	–	130	190	200	–
Meranti, FSC[c]	10	–	6.8	7.5	14	–
Mortar	1	–	1400	1900	1900	–
Multiply	9	–	180	490	460	–
Multiply, FSC[c]	9	–	–	–	240	–
Paper		–	180	230	–	–
Pinewood	10	–	210	380	270	–
Pinewood, FSC[c]	10	–	–	10	87	–
Pinewood, FSC[c], impregnated	10	–	–	–	2000	–
Plastic coating		–	80	–	–	–
Polyamide		–	0.43	1.5	–	–
Polybutylene		–	6.5	9.9	–	–
Polyester		–	2.8	7.8	–	–
Polyester concrete		–	70	70	–	–
Polyethylene, high density		–	17	30	–	–
Polyethylene, low density		–	–	52	47	–
Polypropylene		–	–	2.7	–	–
Polysulfide		–	15	20	26	–
Polyurethane foam, blown with air		–	–	11	–	–
Polyurethane foam, blown with pentane		–	7.5	34	9.9	–
Polyvinyl chloride	17	18	31	38	13	22
Rock wool	7	–	51	65	120	–
Sand		–	–	–	–	61000
Sand mortar	1	2400	4200	6100	–	–
Sand-lime bricks	8	–	17000	21000	2900	–
Stainless steel		–	0.30	52	4.9	–
Steel		480	350	710	94	230
Steel, enamelled		–	320	630	–	–
Steel, galvanized		–	49	160	–	–
Zinc		–	–	–	67	–
Zinc coating		–	0.49	0.65	–	–

[a] Outdoor: Building materials emitting directly to outdoor air (outdoor constructions, part of façades and roofs)
[b] Soil: Materials applied in the soil as to which we assume that the emission to outdoor air during the use phase is negligible
[c] FSC: Forest Stewardship Council label

2 Results

2.1 Material level

In **Fig. 2**, the human health damages due to indoor exposure to contaminants are compared with those due to outdoor exposure for the crawl space and the first floor during the use phase of the building materials. For the second floor, the ratio of damage to human health due to indoor and due to outdoor exposure is about the same as that for the first floor. For materials emitting to the crawl space, health damage due to outdoor exposure is dominant over health damage due to indoor exposure for all building materials except glass wool, rock wool and glued wood. For materials emitting to the first floor, health damage due to indoor exposure is dominant over health damage due to outdoor exposure for all building materials except acrylic wall paint.

In **Fig. 3** and **4**, the human health damage scores per kilogram product applied in the reference dwelling due to the emissions occurring in the use phase and associated with the rest of the life cycle are compared for the crawl space and the first floor. The values used in these figures are given in **Appendix 3** (online edition only <DOI: http://dx.doi.org/10.1065/lca2004.12.194.2.1>). Note that the scales of the axes of Fig. 3 differ from those of Fig. 4. In Fig. 3, the values of material categories 4 and 10 are not given, because the value of the damage score due to the emissions occurring in the use phase is 0 DALY·kg^{-1}. The damage scores due to the emissions occurring in the use phase for emissions to the second floor are roughly the same as those for emissions to the first floor.

The human health damage scores due to the emissions occurring in the use phase for building materials applied in the

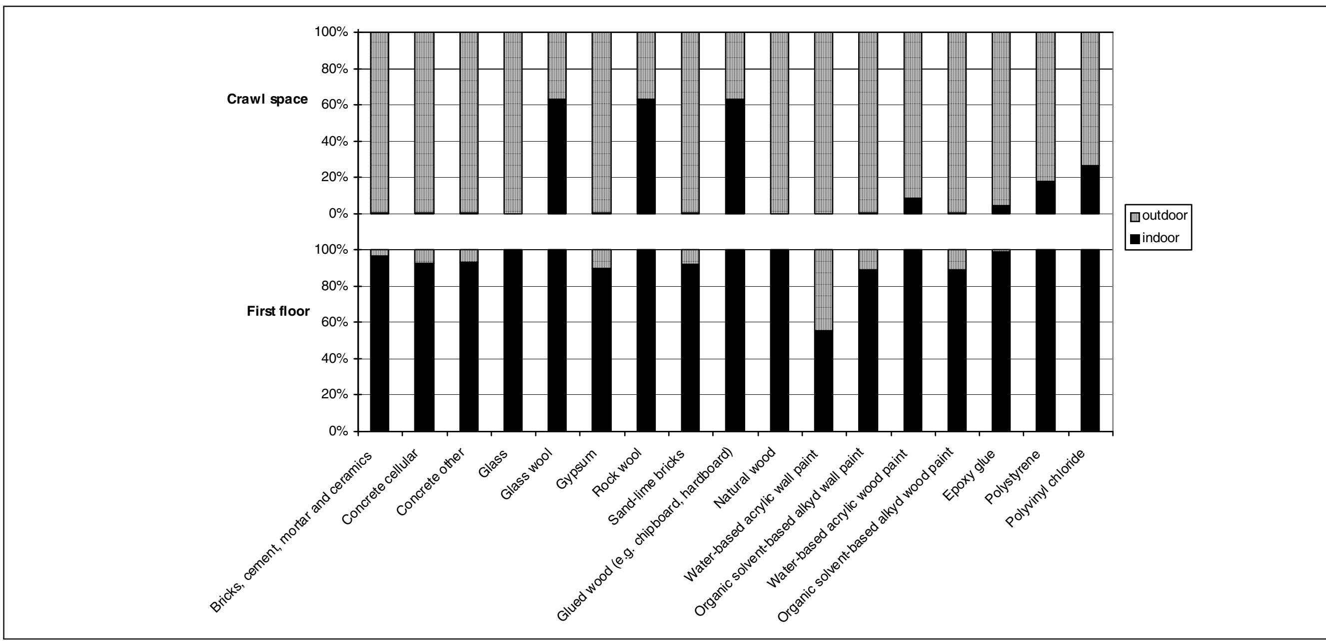

Fig. 2: Comparison of human health damage scores due to indoor and outdoor exposure with substances emitted to the crawl space and first floor during the use phase of the building material

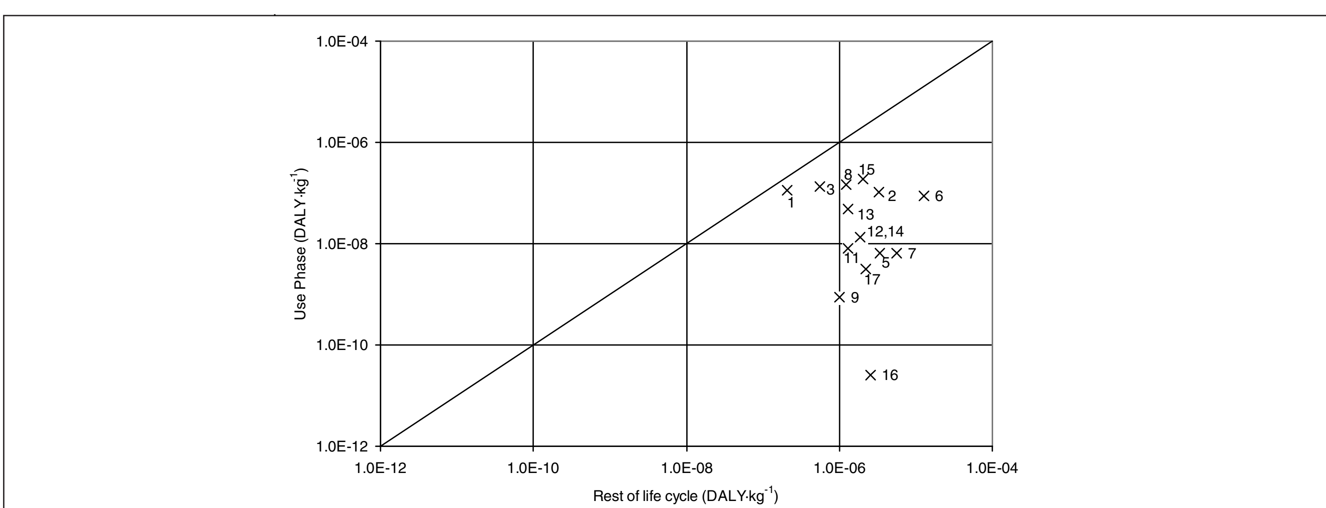

Fig. 3: Comparison between human health damage scores due to the emissions occurring in the use phase and associated with the rest of the life cycle for the crawl space

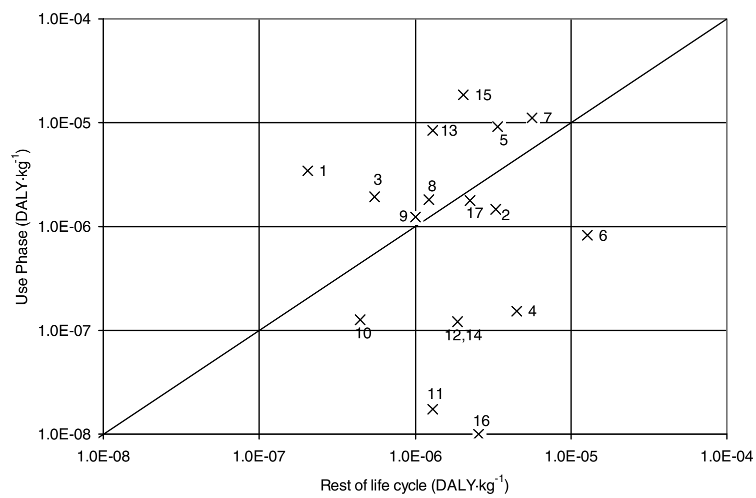

Fig. 4: Comparison between human health damage scores due to the emissions occurring in the use phase and associated with the rest of the life cycle for the first floor

crawl space are roughly a factor 10 lower than the human health damage scores due to the emissions occurring in the use phase for building materials applied at the first and second floor. For building materials applied at the first and second floor, damages scores due to the emissions occurring in the use phase are within about the same order of magnitude as the damage scores associated with the rest of the life cycle.

The contribution of the different contaminants to the human health damage score due to emissions occurring in the use phase is given in **Table 4**.

Regarding the materials that are usually applied in relatively large amounts such as concrete, bricks and wood, radon and formaldehyde have a dominant effect on the damage to

Table 4: Contribution of the different contaminants to the human health damage score due to emissions occurring in the use phase

Material	Substances	Contribution to health damage score due to emissions occurring in the use phase		
		Crawl space	First floor	Second floor
Stony materials				
Bricks, cement, mortar and ceramics	Radon	100%	26%	41%
	Gamma radiation	0%	74%	59%
Concrete cellular	Radon	100%	58%	73%
	Gamma radiation	0%	42%	27%
Concrete other	Radon	100%	55%	70%
	Gamma radiation	0%	45%	30%
Glass	Gamma radiation	0%	100%	100%
Glass wool	Formaldehyde	100%	95%	97%
	Gamma radiation	0%	5%	3%
Gypsum	Radon	100%	84%	91%
	Gamma radiation	0%	16%	9%
Rock wool	Formaldehyde	100%	77%	87%
	Gamma radiation	0%	23%	13%
Sand-lime bricks	Radon	100%	63%	77%
	Gamma radiation	0%	37%	23%
Wooden materials				
Glued wood (e.g. chipboard, hardboard)	Formaldehyde	100%	93%	96%
	Gamma radiation	0%	7%	4%
Natural wood	Gamma radiation	0%	100%	100%
Paints and glues				
Water-based acrylic wall paint	Propylene glycol monomethyl ether	100%	100%	100%
Organic solvent-based alkyd wall paint	Xylene	100%	100%	100%
Water-based acrylic wood paint	2-Butoxy ethanol	66%	80%	80%
	Propylene glycol monomethyl ether	33%	0%	0%
	Triethyl amine	2%	19%	19%
Organic solvent-based alkyd wood paint	Xylene	100%	100%	100%
Epoxy glue	Toluene	100%	100%	100%
Plastics				
Polystyrene	Styrene	100%	100%	100%
Polyvinyl chloride	Vinyl chloride	100%	100%	100%

human health due to indoor exposure. For the second group, toluene, triethyl amine, formaldehyde, 2-butoxy ethanol and xylene have a dominant effect on damage to human health due to indoor exposure. Less important contaminants are propylene glycol monomethyl ether and styrene.

From the damage scores presented in Fig. 3 and Fig. 4, it appears that for each compartment the damage scores of the building materials differ up to a factor of 10^5. Furthermore, human damage scores due to emissions occurring in the use phase of building materials applied in the crawlspace are up to 10^5 times lower than human damage scores due to emissions occurring in the use phase of building materials applied in the other compartments. The damage scores due to emissions occurring in the use phase of building materials applied at the first and second floor are up to 20 times higher or lower than the damage scores associated with the rest of the life cycle of the same building materials. Materials that have a higher damage score as a result of emission to indoor air than the damage score associated with the rest of the life cycle are bricks, concrete, insulation wools, sand-lime bricks, glued wood, acrylic wood paint and epoxy glue.

2.2 Dwelling level

In **Table 5**, the total damages to human health due to the emissions occurring in the use phase of the reference dwelling and health damages associated with the rest of the life cycle of the same reference dwelling are given. For the pollutants considered, the damage to human health due to the emissions occurring in the use phase of the reference dwelling is about equal to the damage to human health associated with the rest of the life cycle of the same dwelling.

Fig. 5 shows that at a dwelling level, the contribution of bulk materials to the total damage to human health due to emissions occurring in the use phase of the dwelling is dominant over the contribution of materials applied in small quantities.

Table 5: Total damage to human health for the reference dwelling

	Damage score (y)	Fraction
Due to emissions occurring in the use phase		
Crawl space	$2.2 \cdot 10^{-3}$	0.5%
First floor	$8.5 \cdot 10^{-2}$	18.6%
Second floor	$1.2 \cdot 10^{-1}$	26.4%
Outdoor[a]	$2.4 \cdot 10^{-3}$	0.5%
Total	$\mathbf{2.1 \cdot 10^{-1}}$	**46.0%**
Associated with rest of life cycle	$\mathbf{2.5 \cdot 10^{-1}}$	**54.0%**

[a] Materials emitting only to outdoor air (e.g. outdoor constructions, part of façades and roofs)

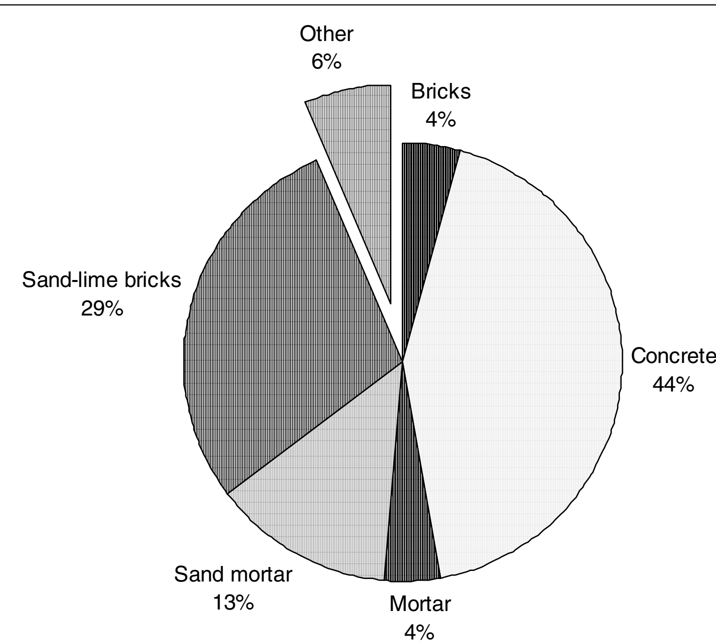

Fig. 5: Main contributors to the total damage to human health due to the emissions during the use phase of the reference dwelling

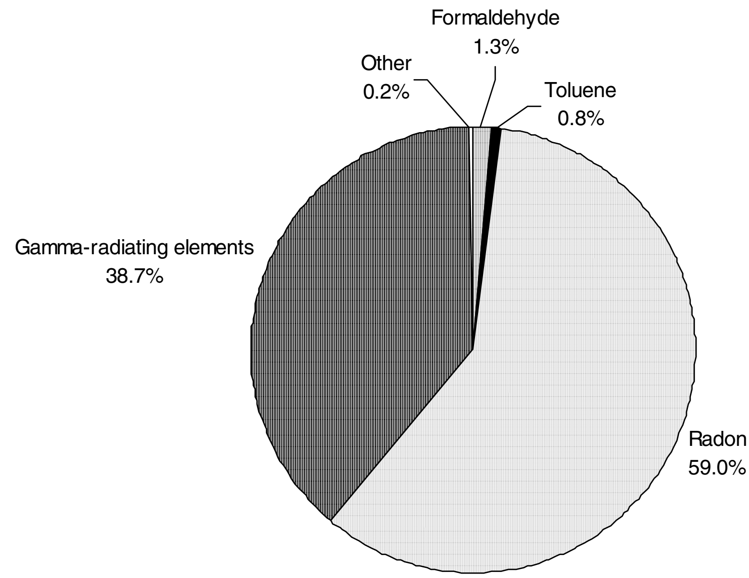

Fig. 6: Contribution of the different contaminants to the total damage to human health due to emissions occurring in the use phase of the reference dwelling

Fig. 6 shows the contribution of the different contaminants to the total damage to human health due to emissions occurring in the use phase of the reference dwelling. Damage to human health at a dwelling level is mainly caused by radon and gamma radiation.

3 Uncertainties and Restrictions

Regarding the damage scores presented here it should be noted that there are several factors causing uncertainties in the emission rate of contaminants from building materials. First, average contaminant concentrations have been used, but within one product group, the concentrations may vary up to one order of magnitude [e.g. 21] and in some cases the contaminant might not be present. The calculations of damage scores can of course be adjusted when the emissions of a specific product differ from the average value. Second, it is assumed that the emission rate of pollutants is essentially constant during the lifetime of the building material. This is true for radon and gamma radiation, but for organic compounds, the emission rate is higher directly after the application of the material. Then the circumstances in the house are often different. For example, the ventilation rate is often higher after painting activity and there may be a relatively low presence of occupants directly after building activities. This leads to an overestimation of the human health damage for these pollutants. At a dwelling level, this is not very important, because the effects of radon and gamma radiation are dominant in the human health damages. Third, the application of finishing materials like wallpaper or paint might decrease the exhalation of organic compounds and radon from the building material under the finish [e.g. 22]. And fourth, pressure differences between indoor and outdoor air caused by wind or mechanical ventilation might influence the emission rate of organic substances and radon. This has not been taken into account in the current analysis.

Furthermore, at a material level, there are uncertainties in the characterisation factors. These are described in the first part of this research [6]. And for the calculations at a dwelling level, there are additional uncertainties regarding the input of materials. These are caused by the use of average construction dimensions and average material densities, as material inputs for the reference dwelling [4,5] are often expressed in terms of areas or volumes rather than weights.

The methodology described in this study has two further limitations. Only pollutants with known effects on human health are considered. Pollutants for which no emission data or toxicological data are available are left out of the assessment. This can cause an underestimation of the total damage to human health. An example of this is the lower damage to human health of organic solvent-based alkyd wood paint compared to the damage to human health of water based acrylic wood paint. This is linked to the absence of reliable data regarding the full impact on health of white spirit, a major ingredient of organic solvent based paints.

The results presented in Fig. 3 and Fig. 4 show that the human damage scores of stony materials are dominated by indoor air emissions. In contrast, human damage caused by the application of wooden materials is much less influenced by the inclusion of indoor air pollution. This implies that the environmental advantages of replacing stony materials by wooden materials in dwellings are underestimated with current life cycle impact assessment methods. Our results also open the possibility to quantify the positive effects on human health of measures to improve the indoor environment like mechanical ventilation. In our approach, mechanical ventilation will result in a lower fate factor for indoor emissions of substances occurring in the use phase of the dwelling and thus in a lower total environmental damage associated with the use phase. It can be concluded from these two examples that for LCIAs applied to dwellings, the

methodology presented in this study results in a more complete assessment due to the incorporation of the benefits of measures to improve the health of the occupants.

The damage scores calculated in this study are representative for single-family dwellings. The (relative) impact of indoor exposure to pollutants emitted to indoor air can be different for other type of buildings (e.g. apartments, offices). The methodology presented in this study [1] can be applied for these types of buildings, but the characterisation factors for the pollutants have to be recalculated.

4 Conclusion

The damage scores of a number of common building materials have been calculated for the Dutch reference dwelling using the fate, effect and damage factor model described in part I of this research [6]. These damage scores were applied to estimate the total damage to human health due to emissions occurring in the use phase of the Dutch reference dwelling. These outcomes were compared with the total damage to human health associated with the rest of the life cycle of the same dwelling.

From these results, it appears that damages to human health due to indoor emissions from building materials of the pollutants considered here cannot be neglected without causing a significant underestimation of total human health damages up to a factor of 20 for the majority of building materials applied at the first and second floor. On a dwelling level, the corresponding underestimation is a factor of 2. Among the pollutants studied here, the main contributors at a dwelling level are radon and gamma radiation. Measures to improve the health of the occupants by improving the indoor air quality result in a lower environmental impact when indoor emissions are taken into account.

For other dwellings, building materials or pollutants, damage scores can be calculated using the methodology described in this study. These damage scores can be used as an addition to standard LCIA data when calculating the environmental impact of dwellings.

App. 3 can be found in the online-edition of this paper
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Appendix 3: Human health damage scores of building materials due to the emissions occurring in the use phase and associated with the rest of the life cycle

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In Table A7, the human health damage scores per kilogram product applied in the reference dwelling due to the emissions occurring in the use phase at the crawl space and the first floor and associated with the rest of the life cycle are given.

Table A7: Human health damage scores of building materials applied in the reference dwelling due to the emissions occurring in the use phase and associated with the rest of the life cycle (DALY·kg^{-1})

Category	Material	Crawl space	First floor	Rest of life cycle
		$DS_{p,c}$	$DS_{p,1}$	$DS_{p,l}$
	Stony materials			
1	Bricks, cement, mortar and ceramics[a]	$1.1 \cdot 10^{-7}$	$3.5 \cdot 10^{-6}$	$2.1 \cdot 10^{-7}$
2	Concrete cellular	$1.1 \cdot 10^{-7}$	$1.5 \cdot 10^{-6}$	$3.3 \cdot 10^{-6}$
3	Concrete other	$1.3 \cdot 10^{-7}$	$1.9 \cdot 10^{-6}$	$5.5 \cdot 10^{-7}$
4	Glass	0	$1.5 \cdot 10^{-7}$	$4.5 \cdot 10^{-6}$
5	Glass wool	$6.6 \cdot 10^{-9}$	$9.1 \cdot 10^{-6}$	$3.4 \cdot 10^{-6}$
6	Gypsum	$8.7 \cdot 10^{-8}$	$8.3 \cdot 10^{-7}$	$1.3 \cdot 10^{-5}$
7	Rock wool	$6.6 \cdot 10^{-9}$	$1.1 \cdot 10^{-5}$	$5.6 \cdot 10^{-6}$
8	Sand-lime bricks	$1.4 \cdot 10^{-7}$	$1.8 \cdot 10^{-6}$	$1.2 \cdot 10^{-6}$
	Wooden materials			
9	Glued wood (e.g. chipboard, hardboard)[b]	$8.8 \cdot 10^{-10}$	$1.2 \cdot 10^{-6}$	$1.0 \cdot 10^{-6}$
10	Natural wood	0	$1.3 \cdot 10^{-7}$	$4.4 \cdot 10^{-7}$
	Paints and glues			
11	Water-based acrylic wall paint	$7.9 \cdot 10^{-9}$	$1.7 \cdot 10^{-8}$	$1.3 \cdot 10^{-6}$
12	Organic solvent-based alkyd wall paint	$1.3 \cdot 10^{-8}$	$1.2 \cdot 10^{-7}$	$1.9 \cdot 10^{-6}$
13	Water-based acrylic wood paint	$4.8 \cdot 10^{-8}$	$8.5 \cdot 10^{-6}$	$1.3 \cdot 10^{-6}$
14	Organic solvent-based alkyd wood paint	$1.3 \cdot 10^{-8}$	$1.2 \cdot 10^{-7}$	$1.9 \cdot 10^{-6}$
15	Epoxy glue	$1.9 \cdot 10^{-7}$	$1.9 \cdot 10^{-5}$	$2.0 \cdot 10^{-6}$
	Plastics			
16	Polystyrene	$2.6 \cdot 10^{-11}$	$9.4 \cdot 10^{-9}$	$2.5 \cdot 10^{-6}$
17	Polyvinyl chloride	$3.2 \cdot 10^{-9}$	$1.8 \cdot 10^{-6}$	$2.2 \cdot 10^{-6}$

[a] $DS_{p,l}$ given for bricks
[b] $DS_{p,l}$ given for chipboard